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Analytical and numerical study on the maximum force developed by a V-beam thermal actuator

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Abstract

The purpose of this paper is to determine and validate an analytical model that will serve as a starting point in the future design of micro-scale V-beam thermal actuators. The influence of its geometrical parameters on the output force was tested while also taking into account the deformation of the substrate. The finite element (FE) studies that were performed on virtual replicas of the V-beam thermal actuator led to the validation of the theoretical model.

Keywords: V-beam thermal actuator; thermal load; influence of substrate thermal expansion.

1. Introduction

V-beam thermal actuators (also called Chevron actuators) are a popular type of thermal actuators due to the uniaxial direction of their output force. The thermal actuation has the benefit of producing relatively large forces and displacements but these performances come at the expense of large input energy and relatively low frequencies

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because of the time necessary to reach thermal equilibrium [1]. The energy consumption and the frequency response of the V-beam thermal actuator are not the subject of this paper. The aspects treated refer to the influence of the actuator's geometrical parameters on its force output while taking into account the thermal expansion of the substrate.

Sinclair MJ [2] presents an analytical model for a V-beam geometrical type thermal actuator, but in this case the actuation elements are heated to a level at which buckling occurs. The influence of the variation of two angles on the output displacements of a vertical-horizontal V-beam thermal actuator is presented by Varona J, et al., in their paper [3]. Luo JK, et al. [4], present a theoretical model for the electro-thermal heating of a micro-spring structure that consists of multiple mirrored V-beam thermal actuators. Some findings related to contoured beams for a better distribution of the temperature field are reported by Sassen WP, et al., in [5].

All of the models presented in the above mentioned references are based on the assumption that the anchors of the actuator are fixed. Due to the fact that these actuators are mounted on a substrate that is not perfectly rigid and not perfectly insulated from the heated beams, a displacement of the anchor appears which leads to an altered output response.

2. Research problem

The geometrical parameters of the V-beam thermal actuator are presented in Fig.1(a). In order to validate the proposed analytical model several geometrical types were compared to a Reference configuration defined by the parameters: beam width – w = 1mm; beam inclination angle – β = 10deg; distance between consecutive beams – d = 10mm; number of beam pairs – n = 3; beam length – l = 26.4mm. The other geometrical types tested are: β 15, β 20; L 21.3, L 31.5; d 15, d 20; w 1.5, w 2; n 4, n 5 and n 6, where the coding represents the parameter that changes in regard with the parameters of the reference beam (e.g. β 15 means that the sample has an inclination angle of 15deg while all the other parameters have the same value as those of the reference beam). All the samples, including the reference one, have the same thickness – t = 1mm.

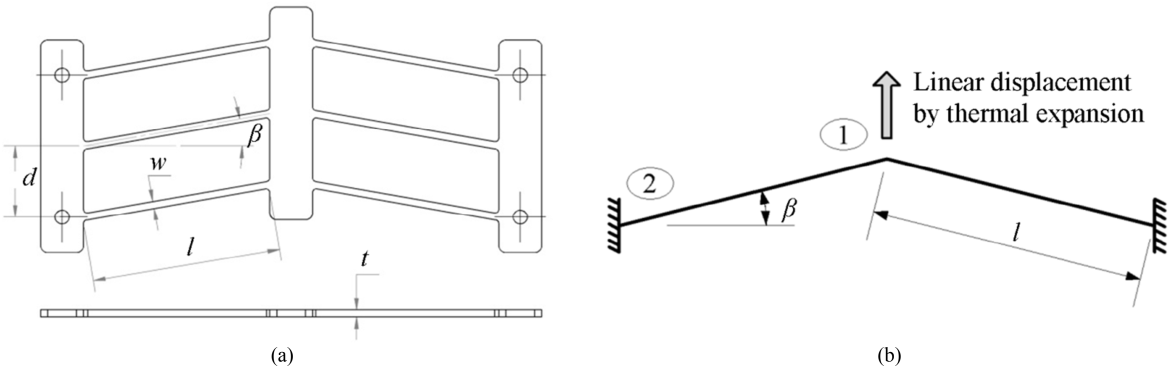

Fig. 1. (a) Geometrical parameters of the V-beam thermal actuator; (b) Theoretical model with boundary conditions.

The theoretical model for a V-beam thermal sensor proposed by Lobontiu N, et al., in [1] is shown in Fig.1(b). As it can be observed, this model also considers the anchors to be fixed. Because of the geometrical and loading symmetry, the problem can be solved for the half model presented in Fig.2(a) by taking into account the internal forces introduced by the missing half.

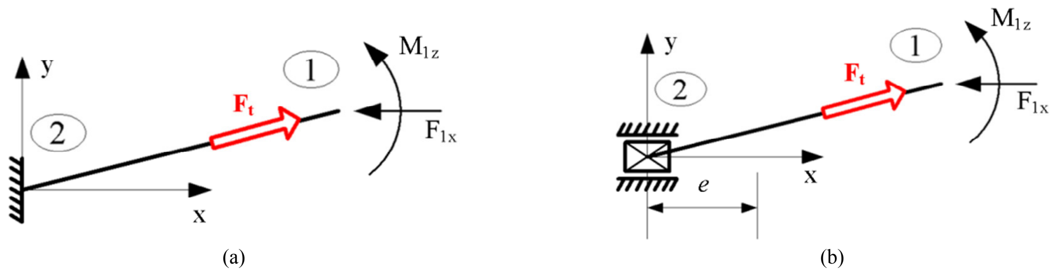

Fig. 2. (a) Half model with thermal load; (b) Half model with thermal load and imposed displacement.

The deformation of the V-beam thermal sensor with imposed displacement along the x-axis presented in Fig.2(b) is given by the equation:

$$u_{1y}^{(Fig.2(b))} = \alpha \Delta T l \sin(\beta) + \frac{\sin(\beta)\cos(\beta)(Al^2 - 12I_z)(e + \alpha \Delta T l \cos(\beta))}{12I_z \cos^2 \beta + Al^2 \sin^2 \beta} \tag{1}$$

in which the terms that weren't previously defined are: α – coefficient of thermal expansion of the sensor's material; ΔT – temperature difference between the initial and final deformed states of the sensor; A – cross-section area of the beam; I_z – moment of inertia of the cross-section of the beam; e – imposed displacement along the x-axis. The imposed displacement can include substrate deformation due to the reaction forces in the anchors, thermal expansion of the substrate or even thermal expansion of the central shaft of the actuator along the x-axis. The results presented later in this paper take into account the last two factors mentioned above.

The details of the experimental and numerical validation of Eq.1 are presented in [6].

In order to determine the deflection of the V-beam thermal actuator when an actuation force is present the overlapping of effects method is used. As shown in Fig.3(a), the resulting deflection can be determined by subtracting the deformation of the structure under the presence of the actuation force with no thermal load from the deformation of the structure under thermal load with no actuation force. The latter deformation is given by Eq.1 while for the determination of the former one the 2nd Castigliano theorem is applied to the model shown in Fig.3(b). The equation for determining the deflection of the structure with actuation force and no thermal load is:

$$u_{1y}^{(Fig.3(b))} = \frac{F_a l^3}{E(12I_z \cos^2 \beta + Al^2 \sin^2 \beta)} \tag{2}$$

in which the terms that weren't previously defined are: F_a – actuation force; E – Young's modulus of the actuator's material.

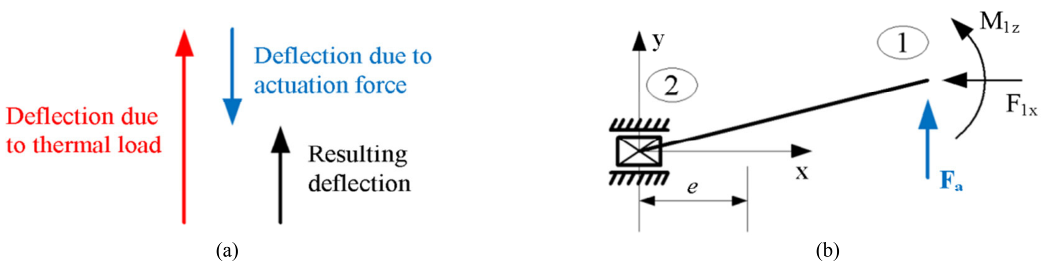

Fig. 3. (a) Resulting deflection determination; (b) Half model with actuation force and no thermal load.

The maximum (blocking) actuation force of the structure is the force that cancels out the deflection due to the thermal expansion of the beams leading to null resulting deflection. The calculus expression for the maximum force, deducted from Eq.2, is:

$$F_{a\_\max} = \frac{u_{\max} E(12 I_z \cos^2 \beta + A l^2 \sin^2 \beta)}{l^3} \tag{3}$$

where u_{max} is the deflection of the geometrical center of the actuator's central shaft (u_{1y} – given by Eq.1) at which the thermal expansion of the central shaft along y-axis is added.

3. Numerical simulation

Finite element (FE) calculations were performed using ANSYS v12 FEA Software for all the above mentioned samples in order to validate the proposed analytical model. The blocking force of the actuator was determined by introducing a null displacement support at the tip of the central shaft. The reaction force of this support (shown in Fig.4) equals the desired maximum (blocking) actuation force.

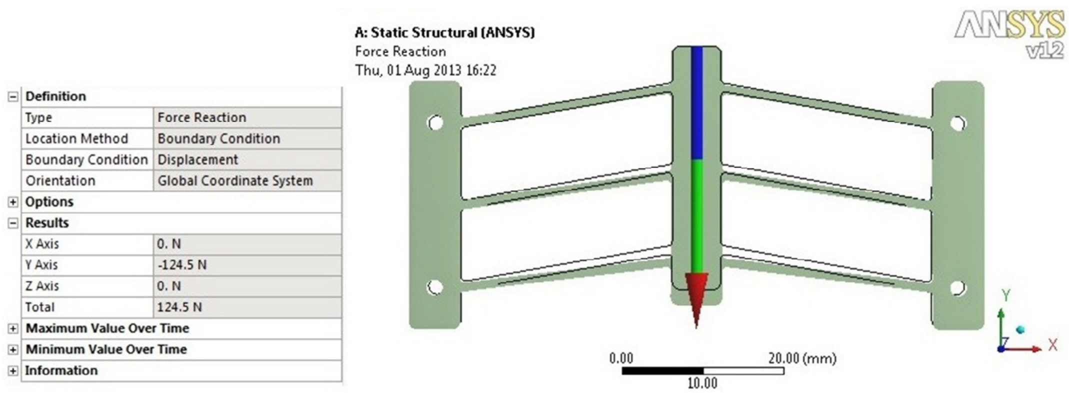

Fig. 4. Maximum force determination by numerical simulation.

The maximum force for the Reference geometrical configuration of the V-beam thermal actuator is shown in Fig.4 (presented above) while the rest of the results are presented in Table 1.

4. Results and conclusions

The comparative analytical and numerical results for the 12 geometrical types of V-beam thermal actuators analyzed are presented in Table 1.

Table 1. Comparative analytical and numerical results.

Sample	Analytical blocking force [N]	Numerical blocking force [N]	Relative error [%]	Sample	Analytical blocking force [N]	Numerical blocking force [N]	Relative error [%]
Ref	120.81	124.50	-3.1	β 15	188.78	182.52	3.3
w 1.5	182.23	181.89	0.2	β 20	261.21	247.70	5.2
w 2	244.85	237.85	2.9	L 60	126.22	125.45	0.6
n4	166.39	168.13	-1.0	L 80	117.26	116.38	0.8
n5	214.63	215.00	-0.2	d 15	124.80	126.50	-1.4
n6	265.51	259.55	2.2	d 20	128.78	130.44	-1.3

The analytical and numerical results are in good agreement, with a relative deviation between the two sets of data of less than 6%, thus leading to the validation of the proposed model. Although the samples studied are macro-scale geometrical types of the V-beam thermal actuator, this is a common Micro-Electro-Mechanical-Systems (MEMS) structure. The proposed model can be used in future optimal design of such structures.

Acknowledgements

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References

[1] Lobontiu N, Garcia E. Mechanics of Microelectromechanical Systems. Boston: Springer, Kluwer Academic Publishers; 2005.
[2] Sinclair MJ. A high force low area MEMS thermal actuator, 7th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, ISBN 0-7803-5912-7, Las Vegas, NV, USA; 2000: 132.
[3] Varona J, Tecpoyotl-Torres M, Hamoui AA. Design of MEMS vertical–horizontal chevron thermal actuators, Sensors and Actuators A: Physical, 153(1); 2009:127-130.
[4] Luo JK, Flewitt AJ, Spearing SM, Fleck NA, Milne WI. Modelling of microspring thermal actuator. Boston: Proc. NSTI-Nanotech, 1; 2004: 355-358.
[5] Sassen WP, Henneken VA, Tichem M, Sarro PM. Contoured thermal V-beam actuator with improved temperature uniformity. Sensors and Actuators A: Physical, 2008; 144(2): 341-347.
[6] Chiorean RS, Dudescu MC, Pustan M, Hardau M. Deflection determination of V-beam thermal sensors using Digital Image Correlation. Proceedings of the 14th Symposium on Experimental Stress Analysis and Materials Testing, Timisoara, Romania; 2013.